Maya: Next Generation Modeling & Simulation Tools for Global Networks

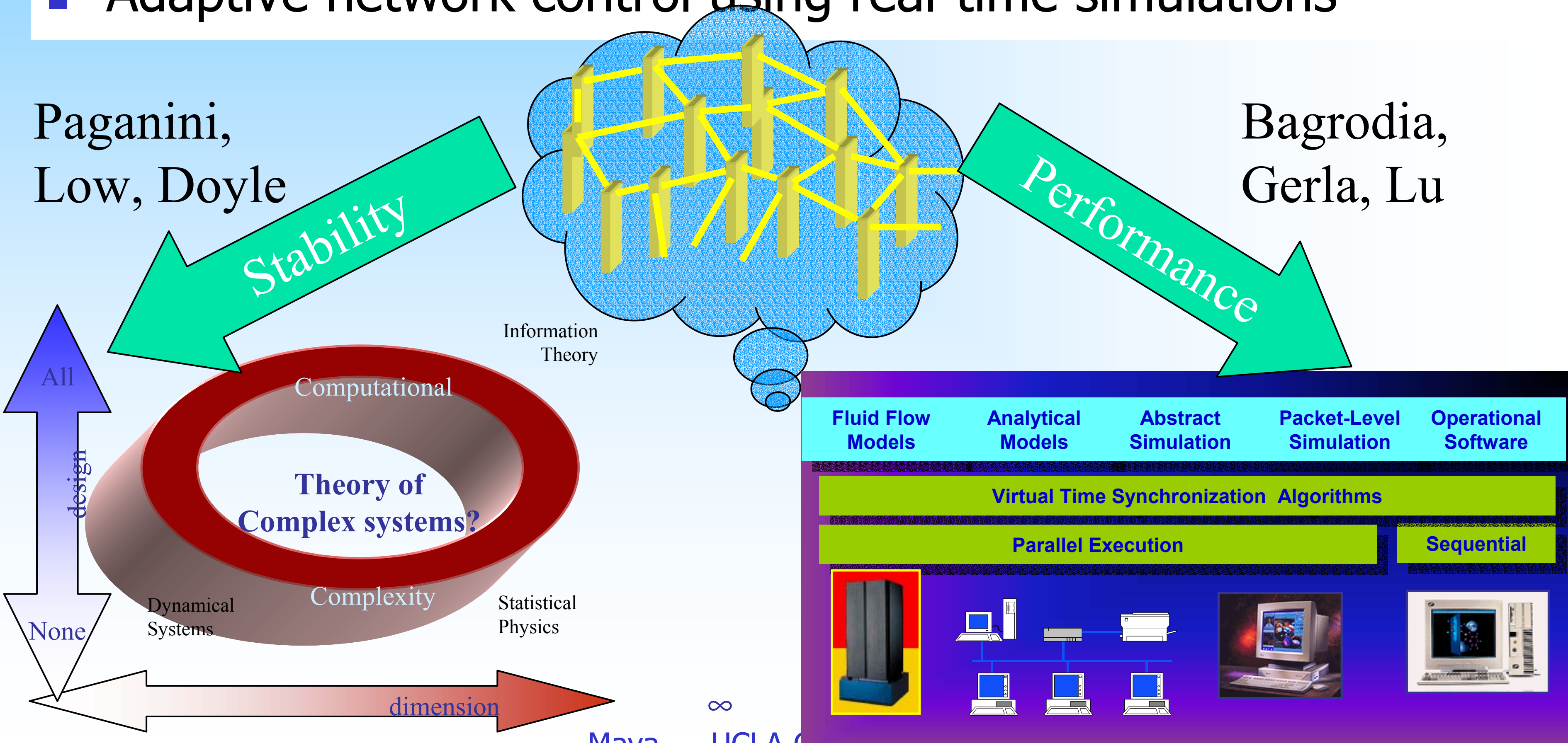
UCLA: R. Bagrodia, M. Gerla, S. Lu, F. Paganini,
M. Sanadidi, M. Takai

Caltech: J. Doyle, S. Low

DARPA PI Meeting, October, 2001
Atlanta

Impact

- A *multi-paradigm* integrated framework for network performance analysis: Maya
- A novel theory of network control and stability: HOT and FAST
- Adaptive network control using real-time simulations

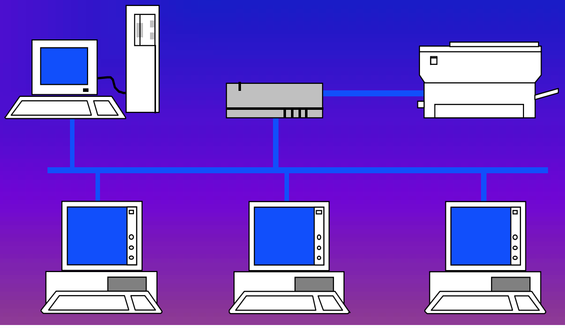


Maya: Multi-Paradigm Network Modeling

Fluid Flow Models	Analytical Models	Abstract Simulation	Detailed Simulation	Operational Software

Virtual Time Synchronization Algorithms

Parallel Execution	Sequential



Multi-Paradigm Network Modeling

- Motivation
  - Achieve appropriate balance between
    - model development time,
    - model accuracy, and
    - model solution time
  - Provides an appropriate validation environment
  - Promotes easier extensibility of models

Accomplishments (Packet Level Simulations)

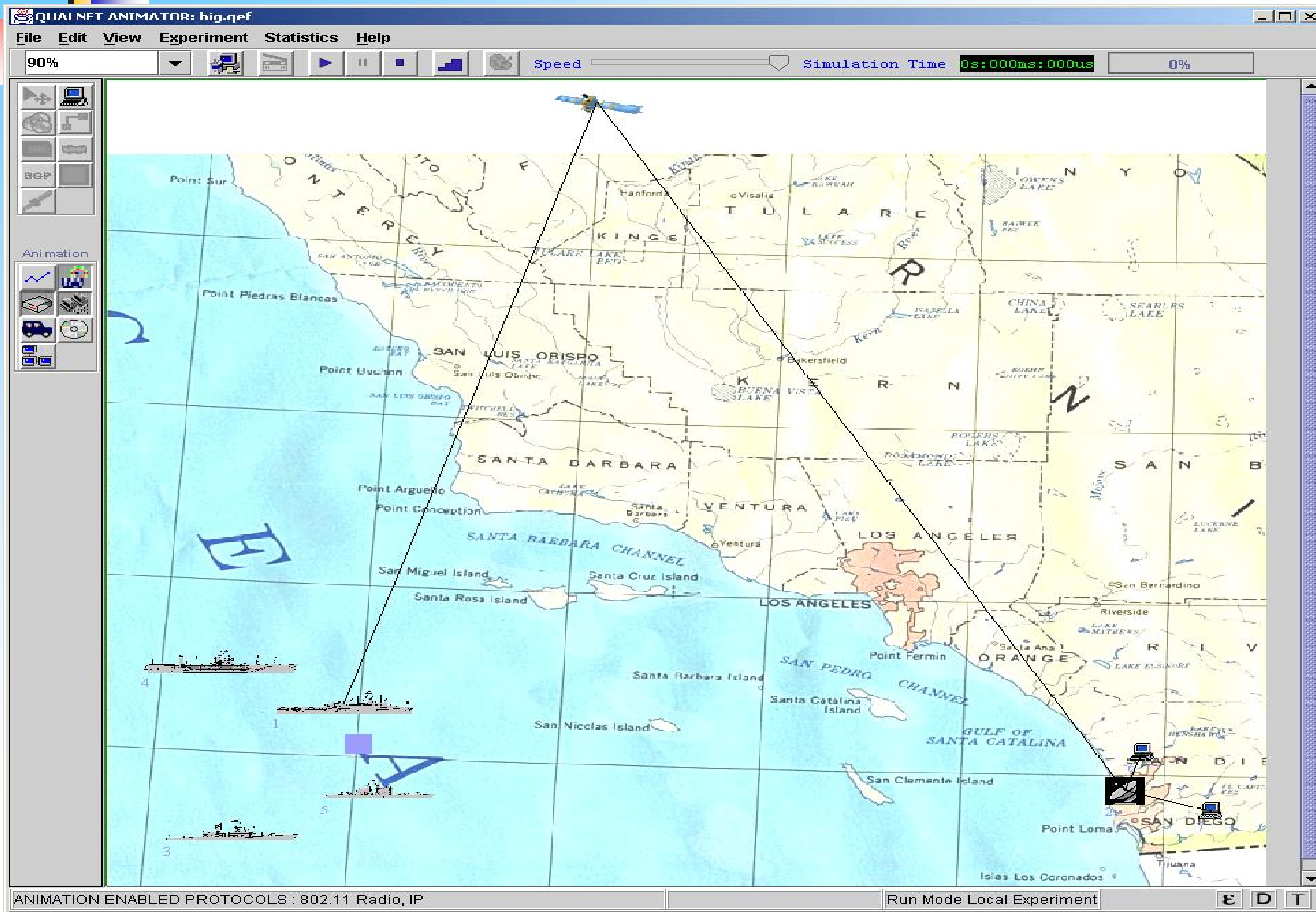
- Simulate realistic Naval scenarios with 65 objects, up to 10x faster than existing COTS tools

- Simulate networks that are 100x larger than can be simulated using existing COTS tools.

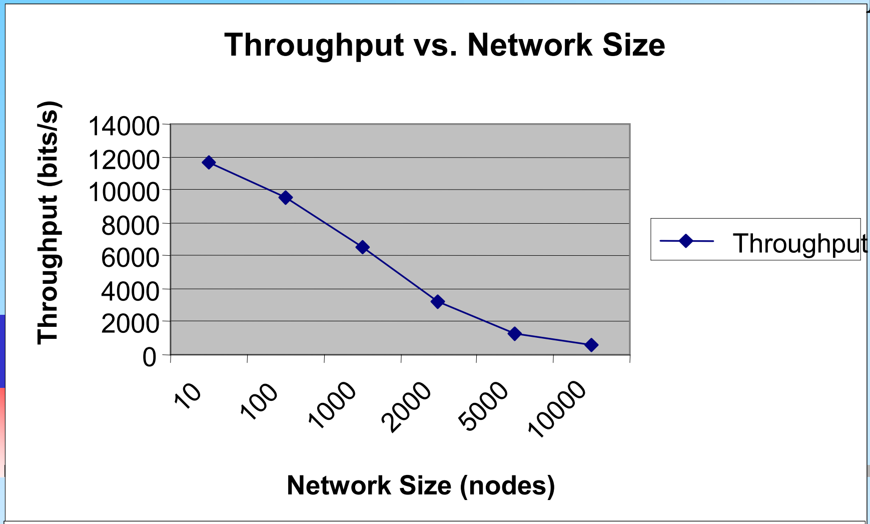
- Accurate simulation of ad hoc networks with 100s of radios faster than real time and detailed simulation of networks with up to 10,000 communication devices.

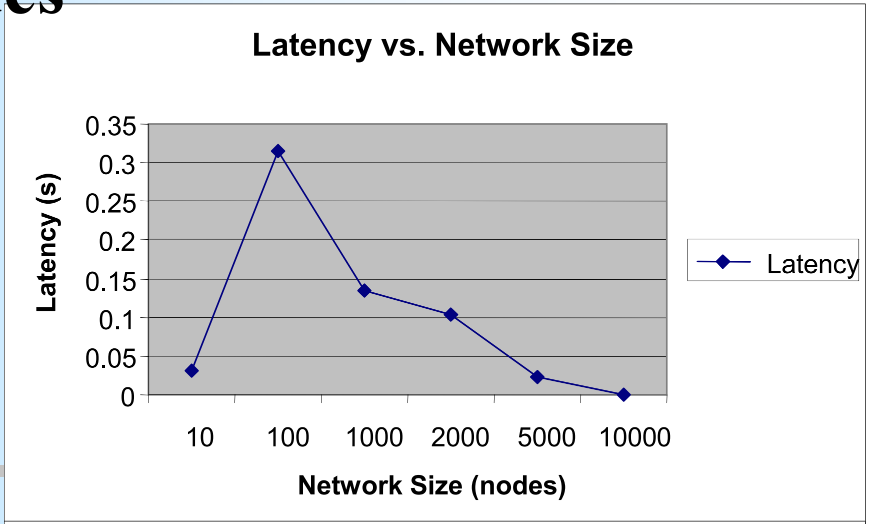
- Technology commercialized into QualNet; in use by DoD units including US Army CECOM, US Navy SPAWAR, and Future Combat System (FCS) to design and analyze next generation military comm networks.

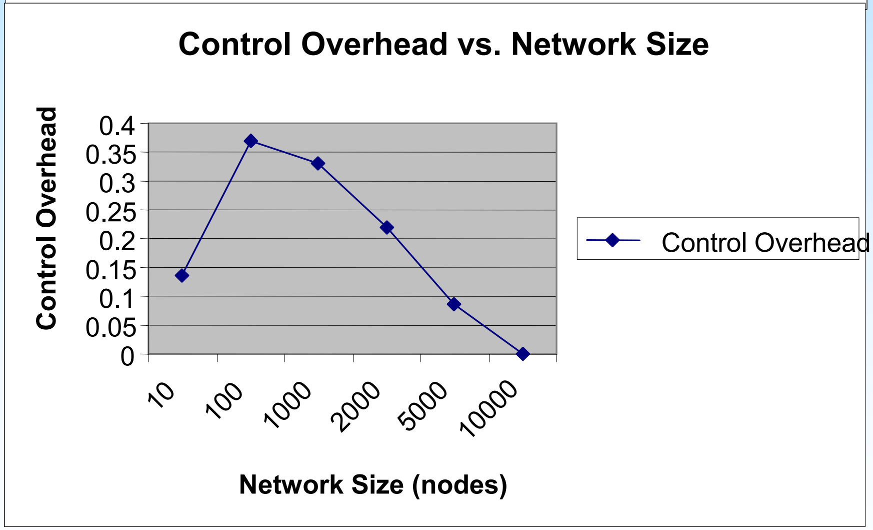
SPAWAR: QualNet Model of Link-16 radios

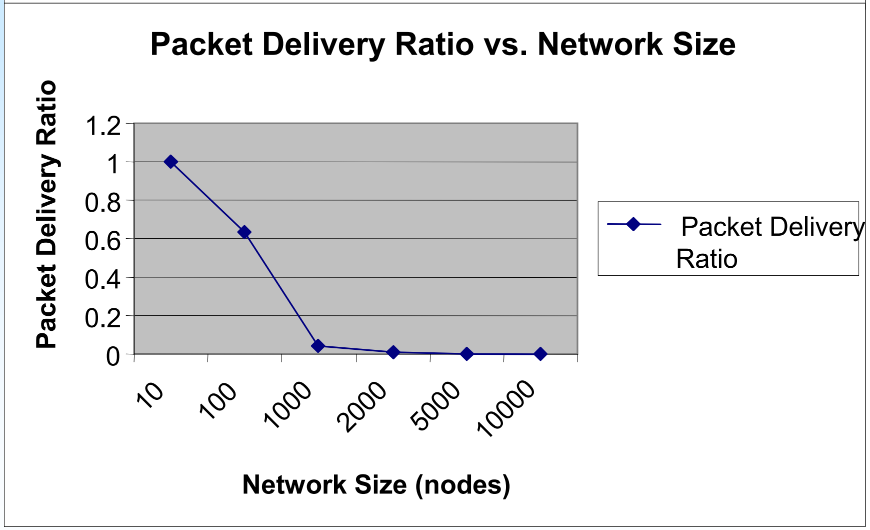


CECOM: Large Ad hoc network simulation:10,000 nodes nodes



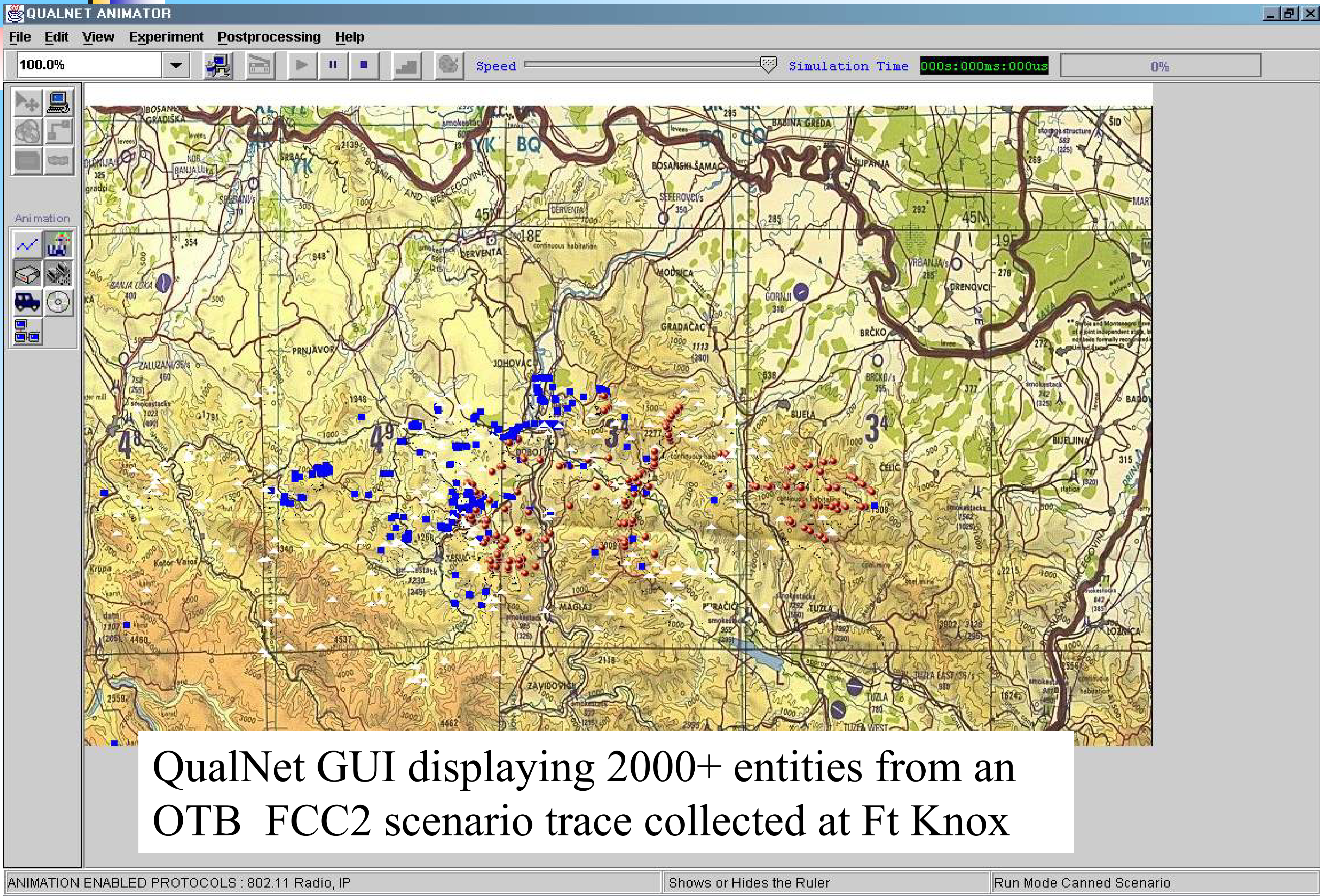






(http://www.msiac.dmso.mil/journal/wong32.html)

CECOM: Integration with WarGaming



QualNet GUI displaying 2000+ entities from an OTB FCC2 scenario trace collected at Ft Knox

Accomplishments (Multi-Paradigm Modeling)

- Integration of fluid-flow models and detailed packet level simulations for TCP Westwood (Demo 1)
  - **Joint work with Gerla & Paganini**
- Integration of fluid-flow models with packet-level simulators NS-2 and QualNet (Demo 2)
  - **Joint work with Amherst & Georgia Tech**
- Integration of operational software with detailed packet-level simulation for distributed applications, using both sequential and parallel execution
- Extended backplane design to directly integrate fluid flow models, discrete-event simulation & operational software

Talk Overview

- Multi-paradigm modeling of TCP Westwood
  - Analytical model based on fluid flow concept
  - Discrete event model based on operational codes
  - Hybrid model that integrate two different modeling paradigms
- Multi-paradigm modeling framework
  - Multiple simulators and analytical models connected via backplane
  - Demonstration overview
- Work in progress with timeframes

TCP Westwood

TCP Westwood (TCPW) controls the window size based on BSE (Bandwidth Share Estimation)

When three duplicate ACKs are detected:

- set ssthresh=BE*RTT

(instead of ssthresh=cwin/2 as in Reno)

- if (cwin > ssthresh) set cwin=ssthresh

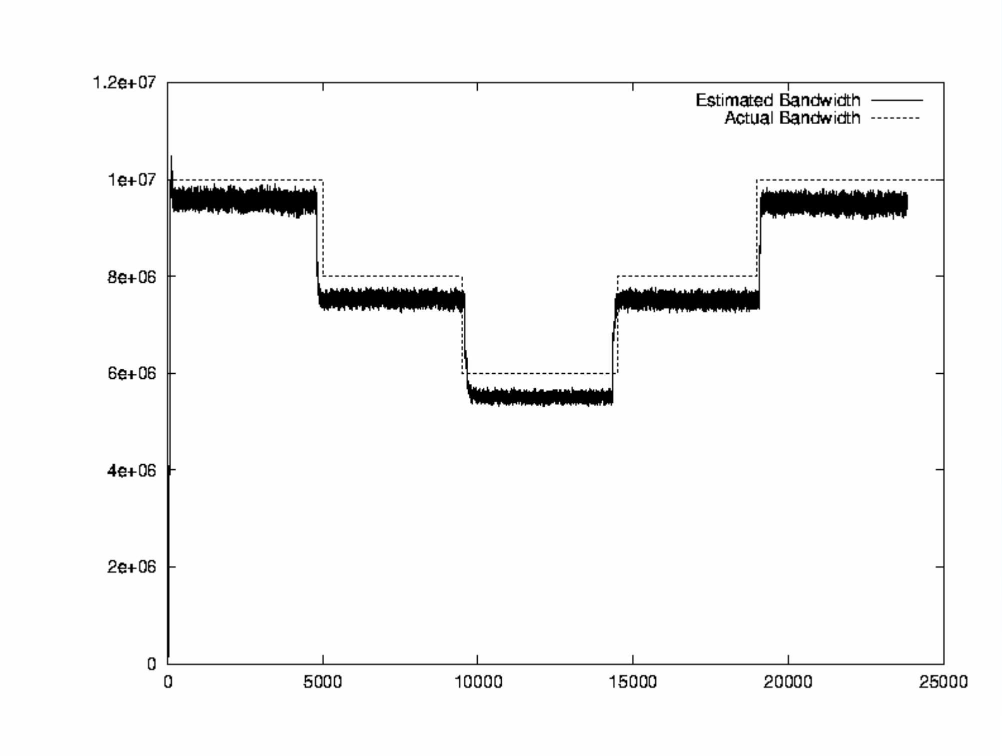
When a TIMEOUT expires:

- set ssthresh=BE*RTT; set cwin=1 ;

(instead of ssthresh=cwnd/2 as in Reno)

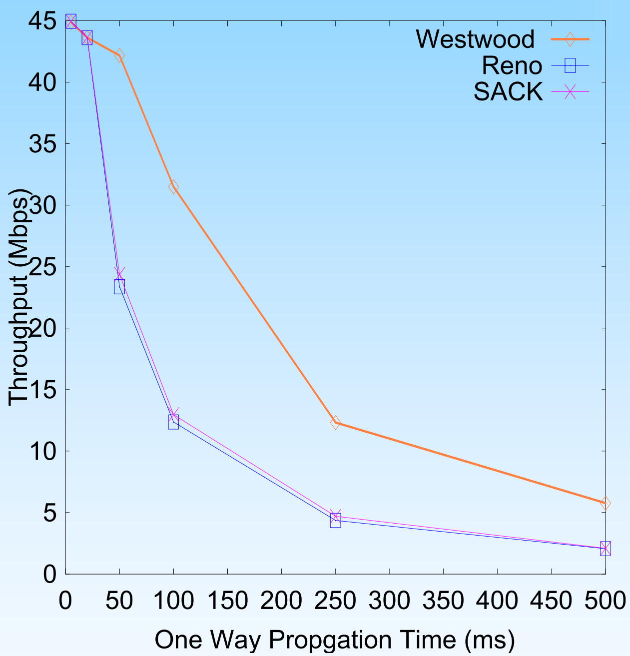
Bandwidth Estimation in TCP Westwood

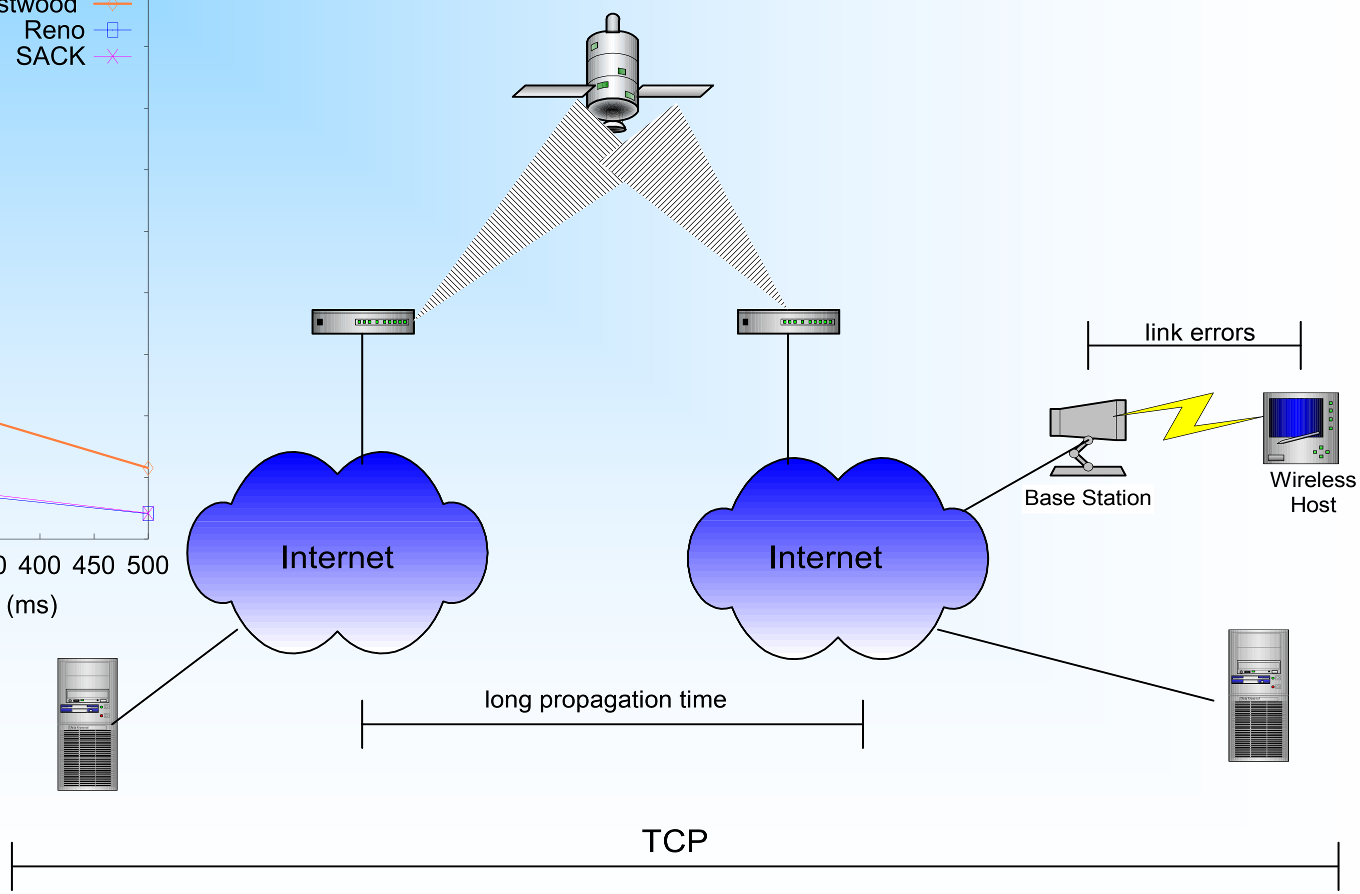
- Estimates Are Determined at TCP Sender Via Sampling and Exponential Filtering Techniques
- Bandwidth Samples Are Determined from ACK Arrival Process and Info Carried in ACKs
- BSE of TCP Westwood with UDP traffic



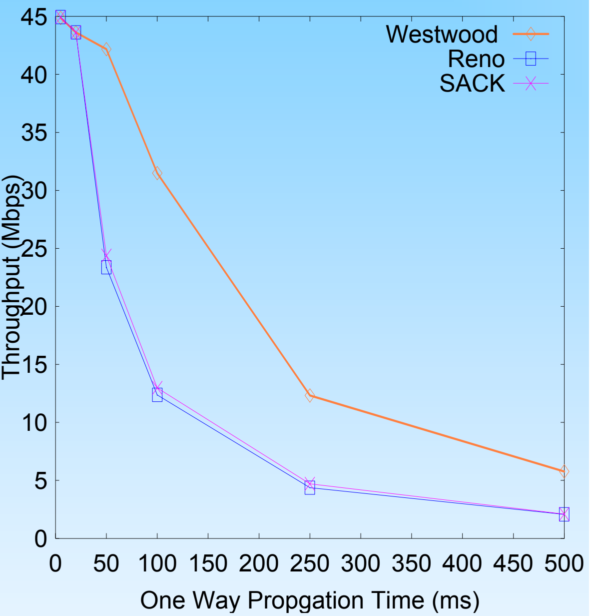
TCP Westwood

- Performance improvements shown for TCP-westwood in links with high loss probability or long delays

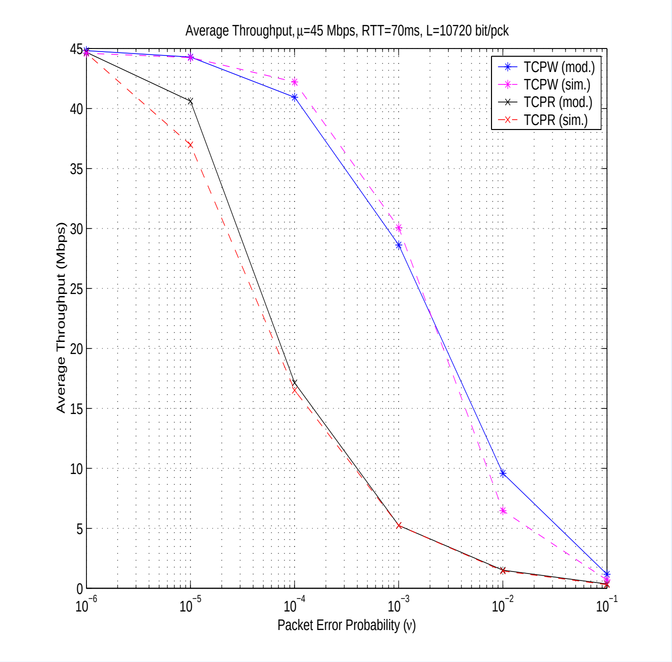




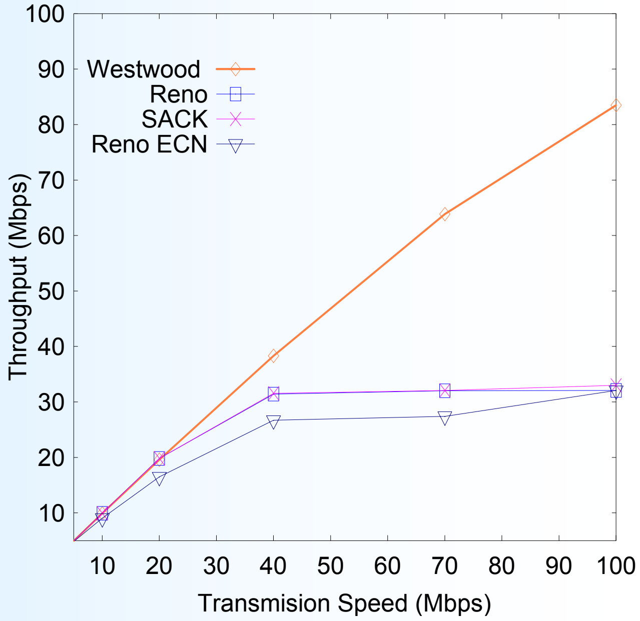
Initial Performance



Simulation



Analysis Validated By Simulation



Simulation

45Mb/s link; 70 msec RTT;

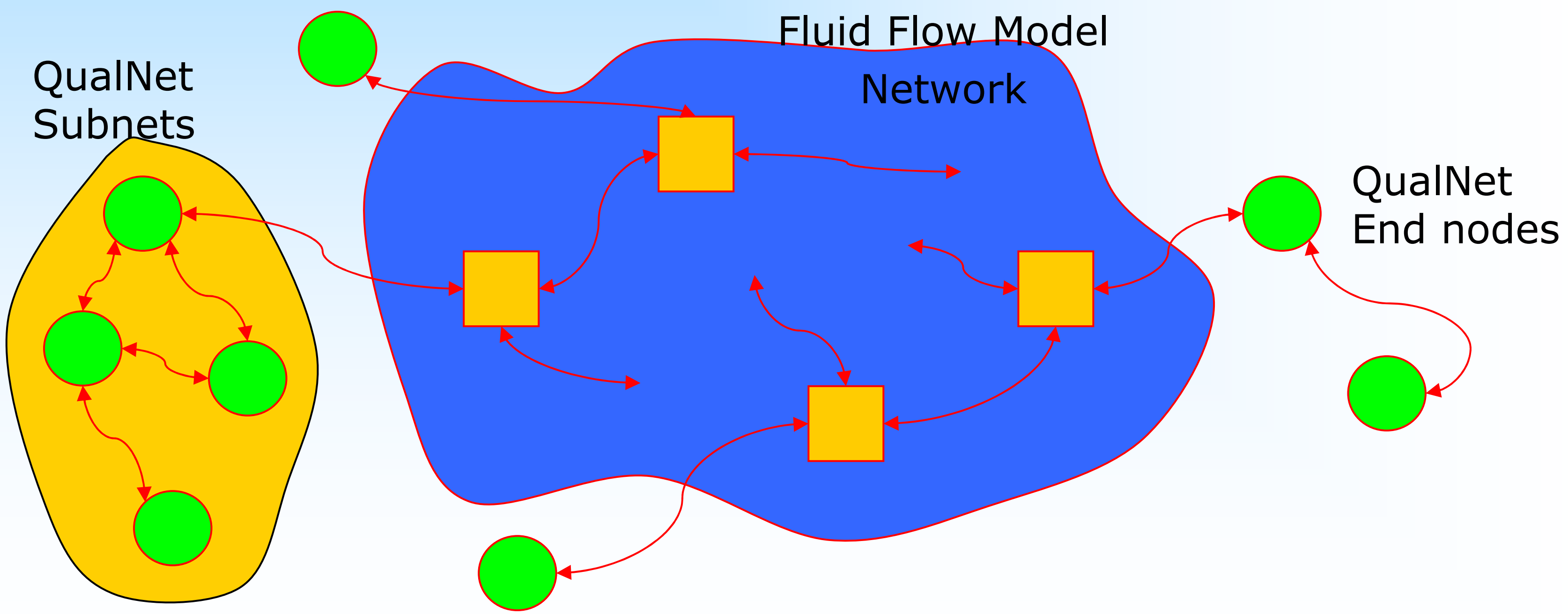
Router Buffer Size=294 (=Pipe Size)

TCP Westwood -- Modeling

- TCP Westwood implemented in QualNet as a variant of TCP models
- Original QualNet TCP models are derived from operational TCP (FreeBSD) codes: validated (highest fidelity)
- Analytical model developed by Paganini et al
- Simulation model by Gerla, Sanadidi, et al
- Mixed analytical-simulation model by Takai, et al

Integration of TCPW Analytical Model and Packet Level Simulator

- Allows more scalability compared to pure packet level simulation
- Designates a wired sub-network of routers to be simulated using analytical model (fluid-flow model)
- Other subnets and nodes are simulated by packet-level simulator (QualNet)



TCP Westwood Analytical Model

- Notations:
  - Wi(t), Ri(t) - Window size and round trip time of ith TCP connection
  - bi(t) - Estimated Bandwidth of ith TCP connection
  - q(t)/C - Queueing delay at congested router
  - p(x) - loss function for AQM policy
  - τ - one round trip delay
- Window size of ith TCP Connection:

TCP Reno

$$\frac{d\overline{Wi}}{dt} = \frac{1}{Ri(\overline{q})} - \frac{\overline{Wi}\,\overline{Wi}(t-\tau)}{2Ri(\overline{q}(t-\tau))} p(x(t-\tau))$$

TCP W'wood

$$\frac{d\overline{Wi}}{dt} = \frac{1}{Ri(\overline{q})} - \frac{\overline{Wi}(t-\tau)}{Ri(\overline{q}(t-\tau))} p(x(t-\tau))[\overline{Wi} - ai \cdot \overline{bi}(t)]$$

- Queue Length estimate: $$\frac{d\overline{q}}{dt} = -C + \sum_{i=1}^{N} \frac{\overline{Wi}}{Ri(\overline{q})}$$
- Average Queue Length is an exponential average:

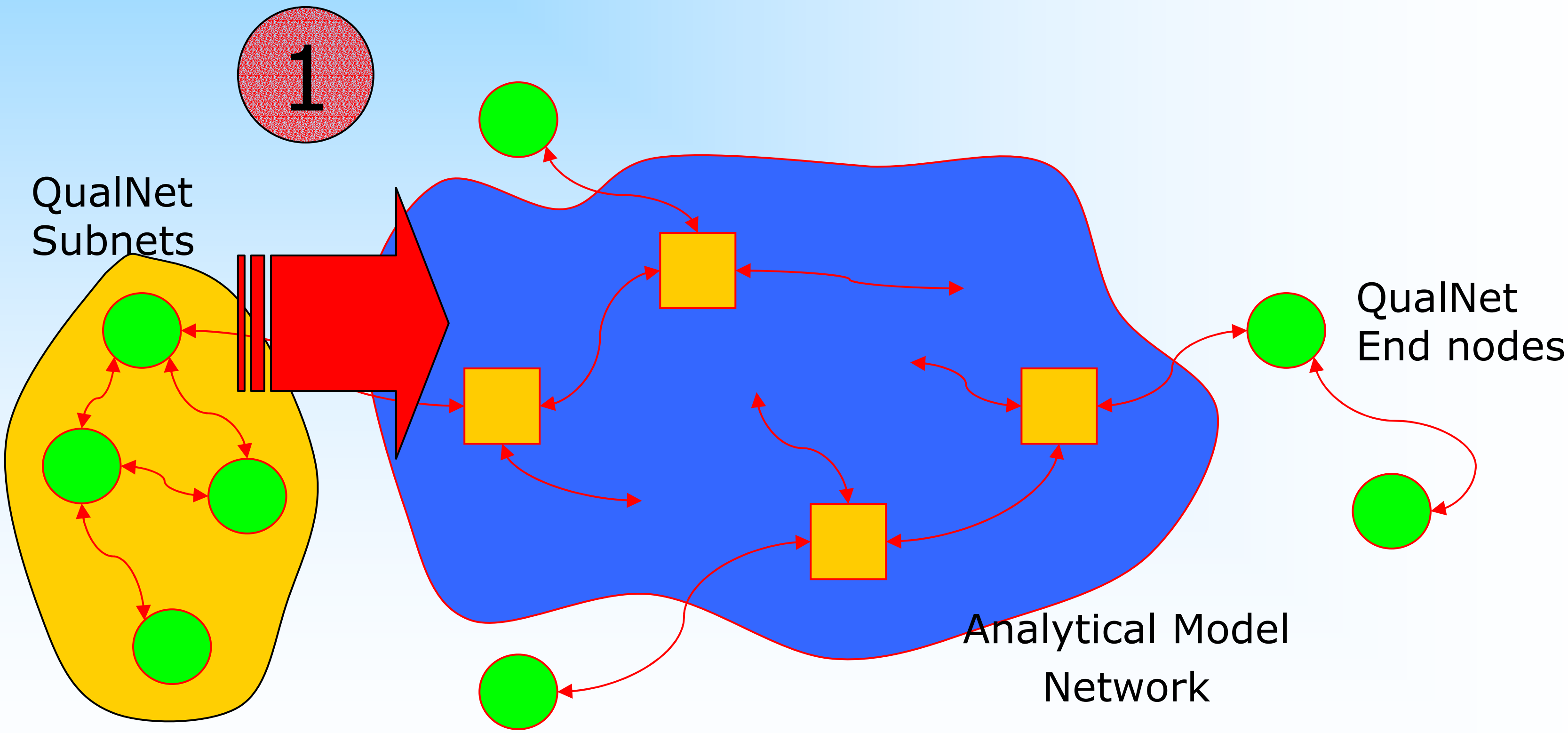
$$\frac{dx}{dt} = \frac{\ln(1-\alpha)}{\delta}\overline{x}(t) - \frac{\ln(1-\alpha)}{\delta}\overline{q}(t)$$

- Bandwidth Estimation for the ith TCP Connection:

$$\frac{d\overline{bi}}{dt} = \frac{1}{T} \cdot \frac{\overline{Wi}(t-\tau)}{Ri(\overline{q})} - \frac{1}{T}\overline{bi}(t)$$

Integration Steps (1)

1. For each link from QualNet nodes to analytical section, packets entering the section will be accumulated as input data rates in each time interval:



Integration Steps (2)

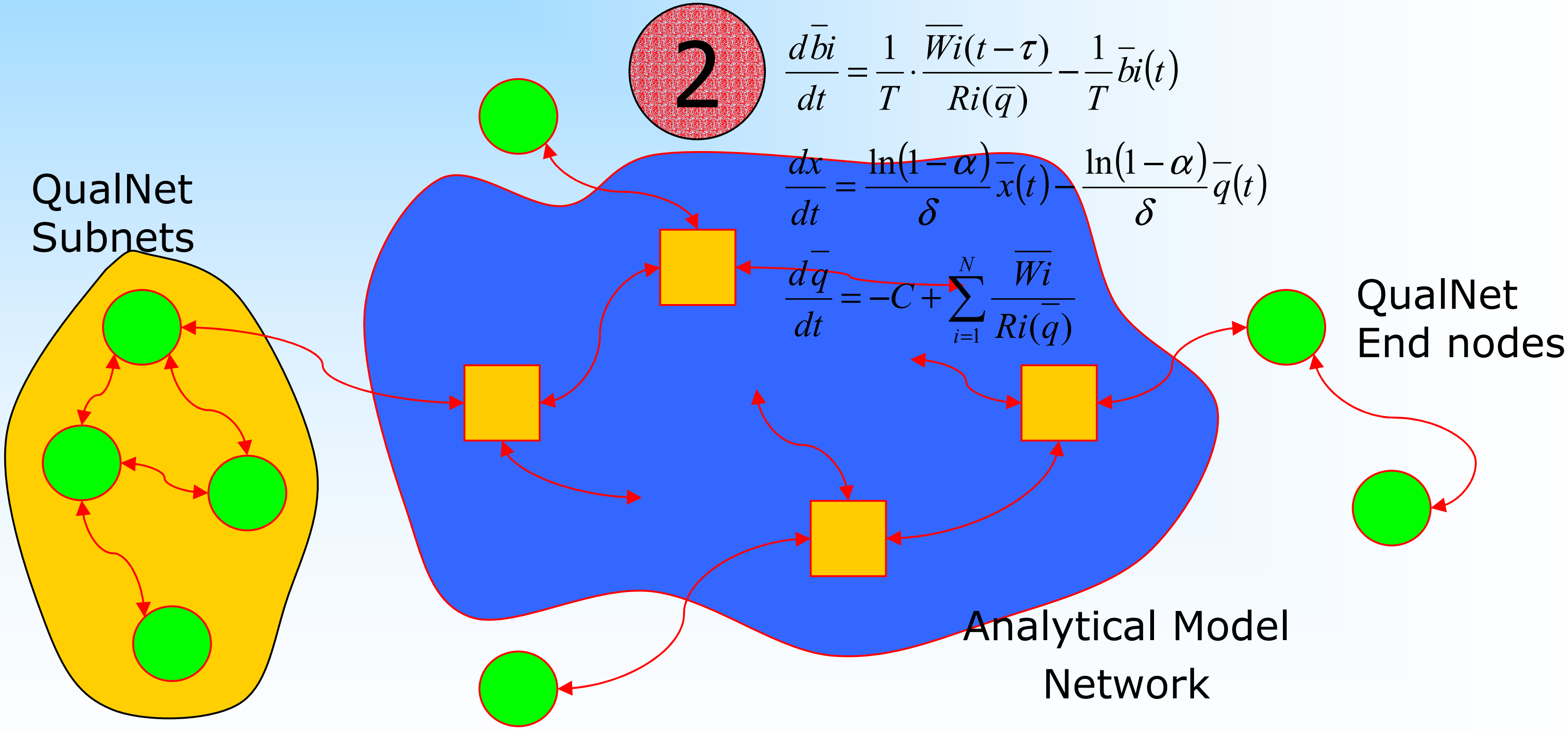
2. The analytical model will solve differential equations to obtain network parameters such as queue lengths of routers:

$$\frac{d\overline{Wi}}{dt} = \frac{1}{Ri(\overline{q})} - \frac{\overline{Wi}(t-\tau)}{Ri(\overline{q}(t-\tau))} p(x(t-\tau))[\overline{Wi} - ai \cdot \overline{bi}(t)]$$

$$\frac{d\overline{bi}}{dt} = \frac{1}{T} \cdot \frac{\overline{Wi}(t-\tau)}{Ri(\overline{q})} - \frac{1}{T}\overline{bi}(t)$$

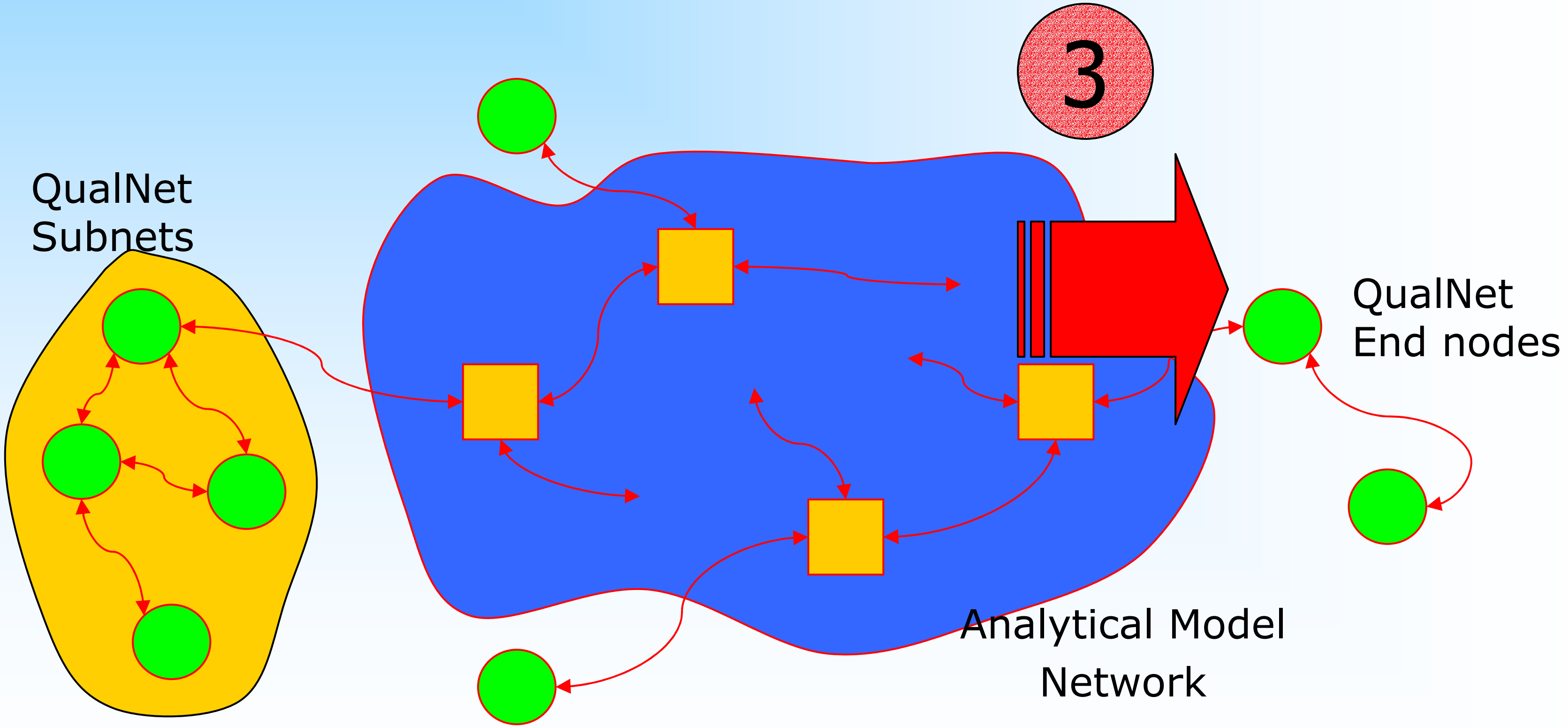
$$\frac{dx}{dt} = \frac{\ln(1-\alpha)}{\delta}\overline{x}(t) - \frac{\ln(1-\alpha)}{\delta}\overline{q}(t)$$

$$\frac{d\overline{q}}{dt} = -C + \sum_{i=1}^{N} \frac{\overline{Wi}}{Ri(\overline{q})}$$



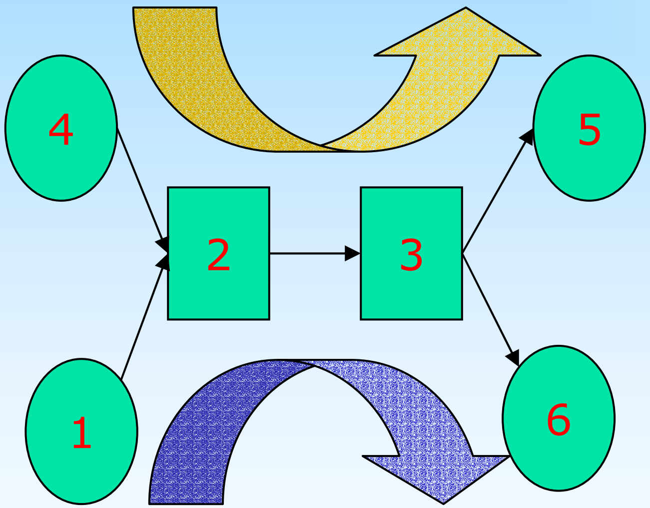
Integration Steps (3)

3. QualNet will estimate delays for each packet based on router queue lengths, then schedule packet arrival events at exit nodes at other side of analytical section:

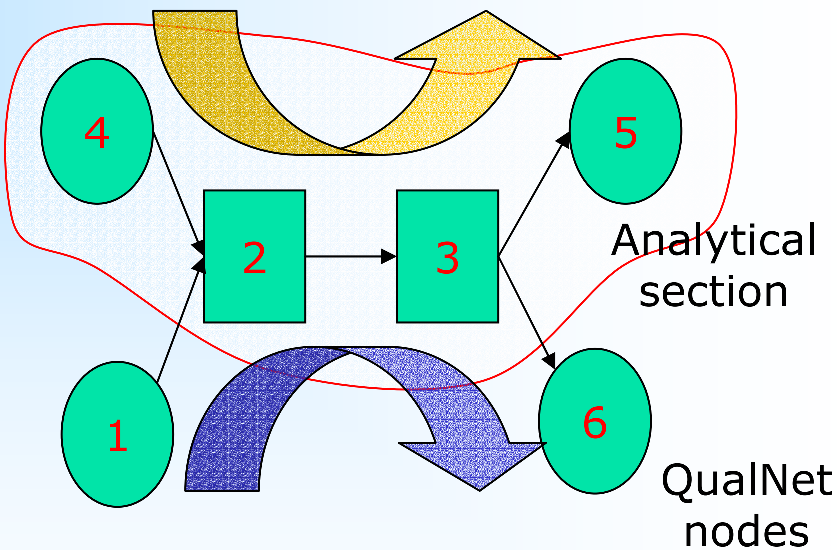


Network Topology for Experiment

- QualNet nodes: 1, 6; Analytical section: nodes 2,3,4,5
- Analytical model Connection: Node 4 ⇨ Node 2 ⇨ Node 3 ⇨ Node 5
- QualNet Connection: Node 1 ⇨ Node 2 ⇨ Node 3 ⇨ Node 6
- Link between nodes 2 and 3 will be bottleneck



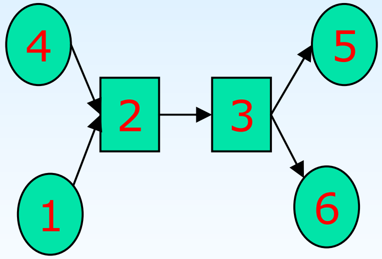
Pure Discrete Event Simulation



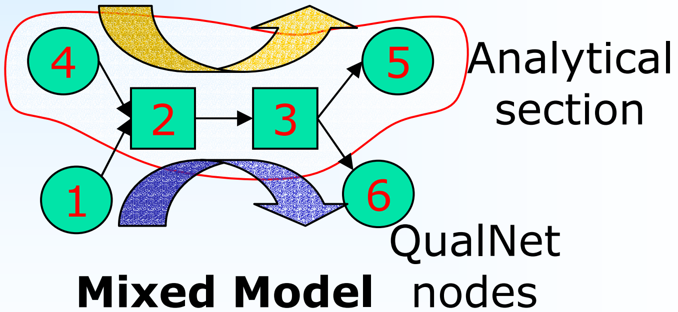
Mixed Model Simulation

Validation

- Connections:
  - 20 TCP Westwood connections from nodes 4 to 5
  - 1 TCP Westwood connection from nodes 1 to 6
- To observe:
  - Comparable transient and average queue lengths at a specific node for both models



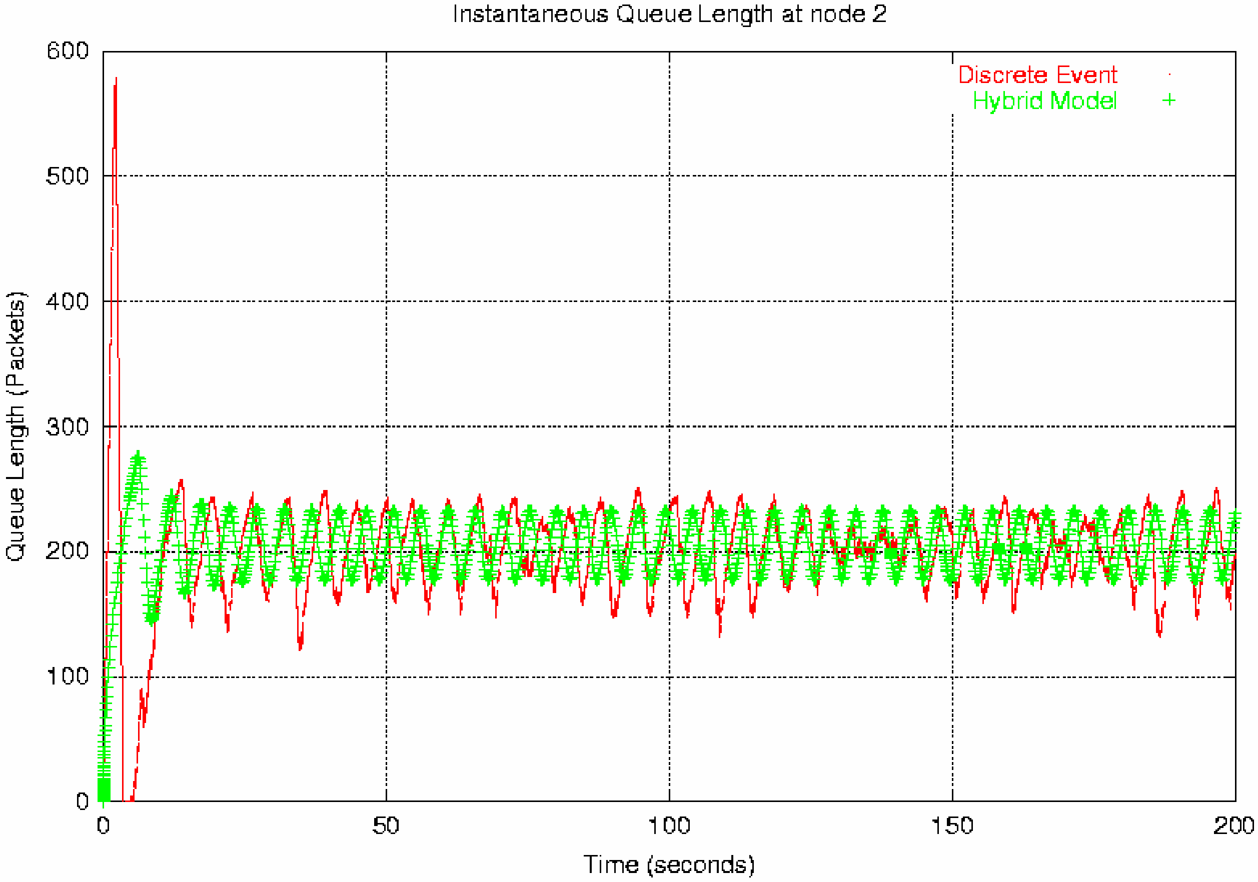
Pure Discrete Event Simulation



Mixed Model Simulation

Validation (2)

- The oscillations stabilize quickly
  - Both models produce almost the same average queue lengths over a short period of time

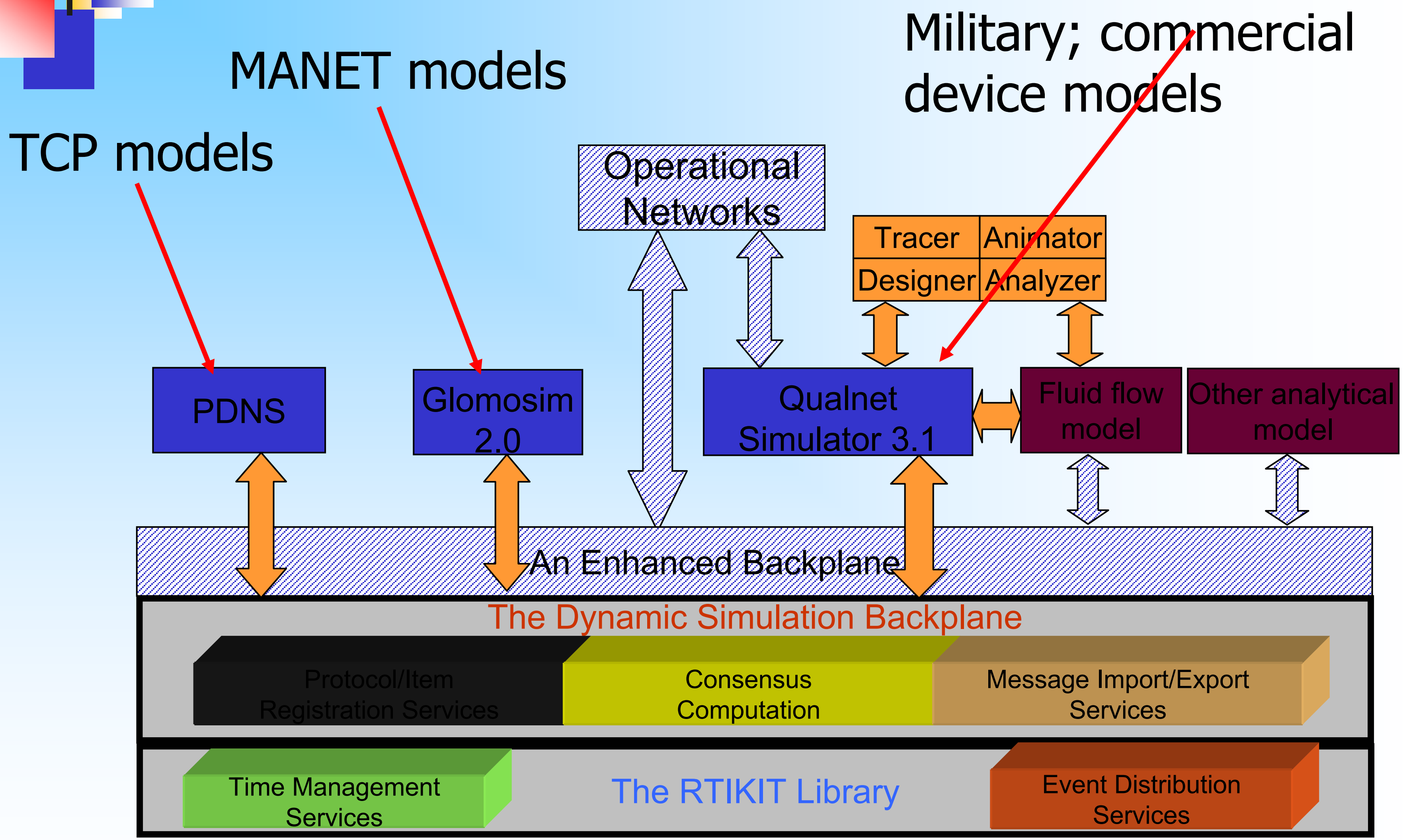


Validation (3)

- Greater differences at the beginning of the simulation
  - This is due to the lack of slow start for the analytical model

- After a few seconds, the oscillations stabilize and both curves look similar
  - Both models produce almost the same average queue lengths over a short period of time
  - This shows that analytical model makes quite good predictions

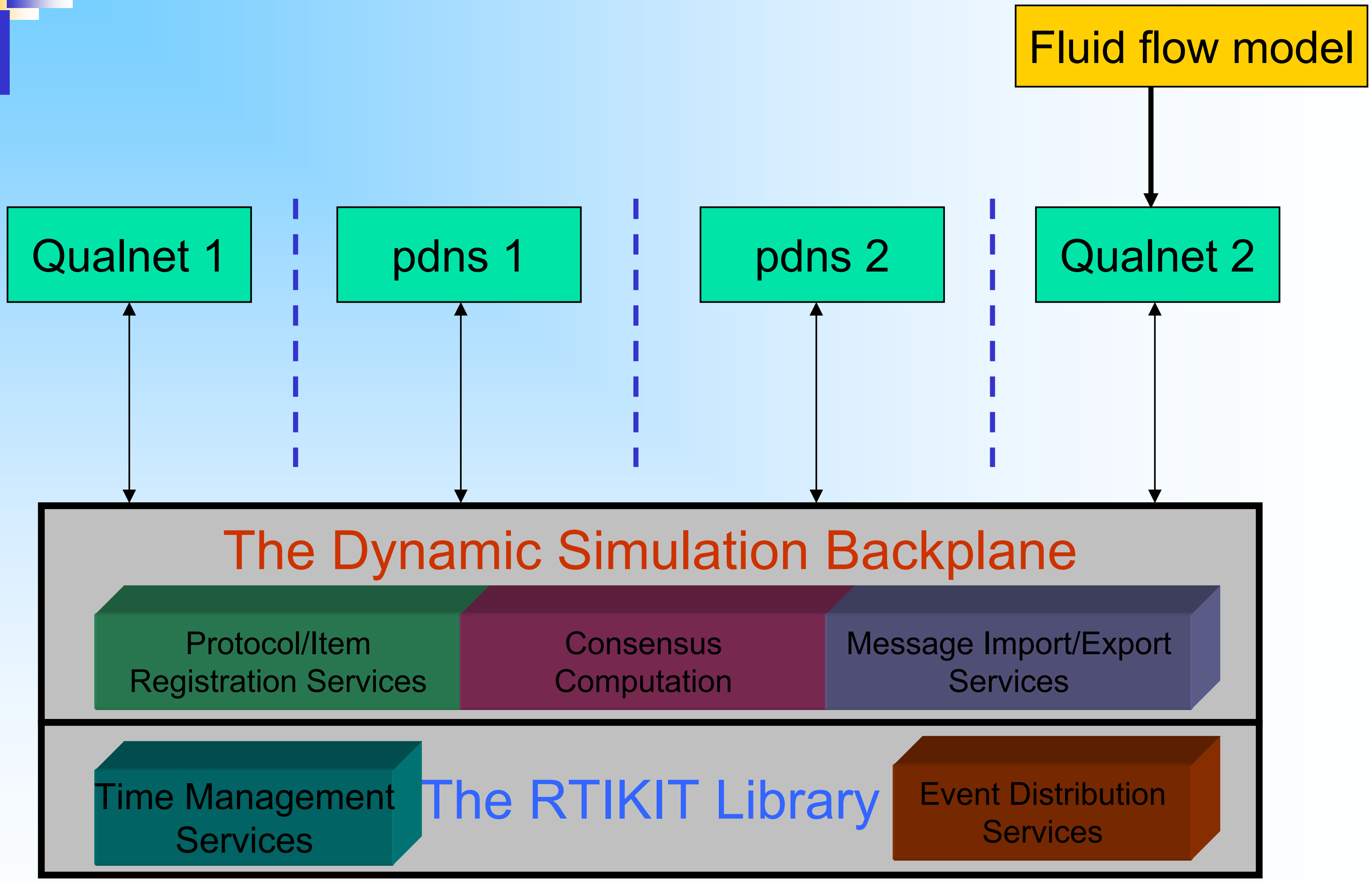
Multi-Paradigm Modeling Framework



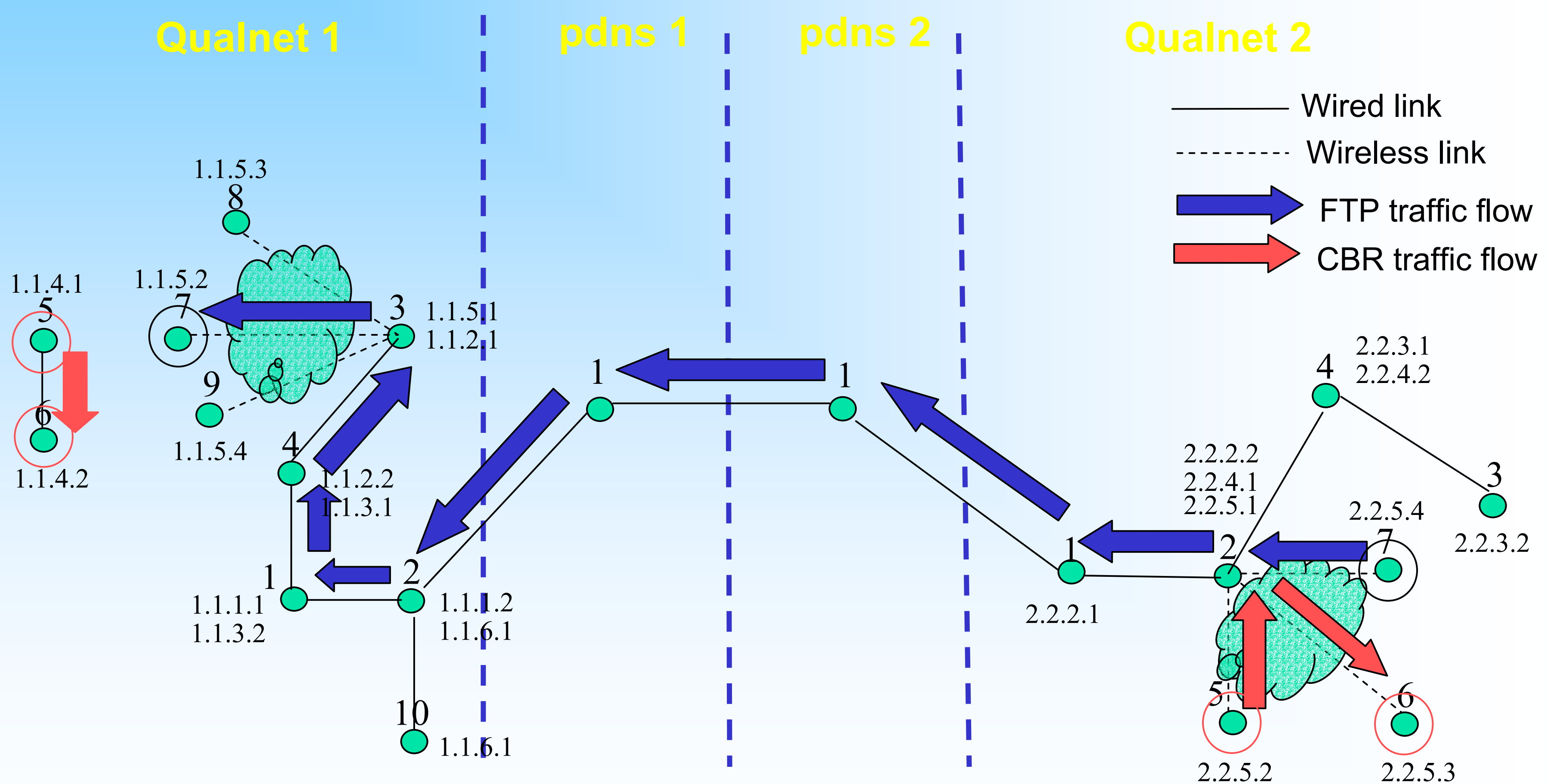
Distributed Network Simulation: Approach

- Partition the network to be simulated into sub-networks.
- Each sub-network is simulated by one simulator instance.
- The simulator instances are inter-connected via a dynamic simulation backplane
- The simulator instances exchange messages at runtime through the backplane to model packet transmissions across sub-networks.

Current Implementation



Demo Overview



Future Work

- Hybrid model (mix of analytical and discrete event models) has been implemented and verified with pure discrete event models
  - Extend model to derive end-end latency & throughput
  - Extend model to networks with hundreds of flows
  - Generalize interface to incorporate diverse fluid flow models
  - Extend model to incorporate parallel DES
- Multi-Paradigm modeling Environment
  - An enhanced dynamic simulation backplane that supports more generic network topologies
  - Incorporation of analytical network modeling tools such as fluid flow based TCP models
  - Incorporation of operational software